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GRAVEL DISPERSION ON A GRANITE PEDIMENT (EAST MOJAVE DESERT, CALIFORNIA): A SHORT-TERM LOOK AT EROSIONAL PROCESSES

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ABSTRACT

Hypotheses about the influence of surface shape, landscape unit and vegetation cover on gravel dispersion were tested on a shallowly dissected portion of a low-sloping granite pediment in the East Mojave Desert of California. Painted gravels (2 to 20 mm diameter) were placed at 117 nodes on a 6 m × 3 m grid. Gravel movements were recorded after 9·7 cm of precipitation over a four-month period. Vectors indicating the magnitude and direction of gravel movement were longest for summits (24 cm, 34 nodes observed) and shortest for backslopes (14 cm, 27 nodes observed). Gravels beneath shrub canopies were protected significantly from rainsplash transport. To describe dispersion symmetry, eccentricity values were calculated using a ratio of variances of major and minor axes of an ellipse. Mean eccentricity values ranged from about 3 to 250 with dispersion on summits being the most symmetrical and dispersion in washes being the most elongated. Erosion is the most important soil- and pediment-modifying process at upper elevations of the Granite Cove Pediment which is cut off from sediment additions because of washes incised at the base of the mountain front. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS desert soils; erosion, granite pediment; Mojave Desert; painted particles

INTRODUCTION

The general goal of this and associated studies (Edinger, 1990) was to test hypotheses about soil- and pediment-modifying processes occurring on a smooth, low-sloping pediment derived from granite rocks in the East Mojave Desert of California. Few systematic experiments in soil genesis have been performed on granite pediments, in part because of their erosional character; they do not lend themselves to classic monovariant state factor analysis (i.e. chronosequence studies). The objective of this paper was to develop descriptive statistics to quantify gravel dispersion and movement after several rainfall events at the upper elevations of the pediment, where low relief has developed.

Developing methodology to evaluate and depict surface movement of gravel-sized particles is no simple task. Fluvial geologists have used painted cobbles and other preparations to trace sediment transport in stream beds (Leopold *et al.*, 1966; Keller, 1970). Others have used radioactive isotopes to trace soil particle movement from simulated and natural rainsplash (Coutts *et al.*, 1968a, b). The characteristics of particle movement are important to archaeological observations (Reid and Frostick, 1985). The method used in this study involved painting 'native' gravels and charting their movement.

The erosion experiment described in this study did not address long-term pediment formation directly. While Baker (1988) encouraged a 'geomorphogenetic' approach to the study of pediments, using larger temporal and spatial scales, this study used a 'geomorphotechnical' approach because we had a different aim. We wanted to understand why and how a complex pattern of soil taxa had been obscured beneath a relatively smooth, low-sloping surface over more intermediate and recent temporal scales than the pediment landform's formation as a whole.

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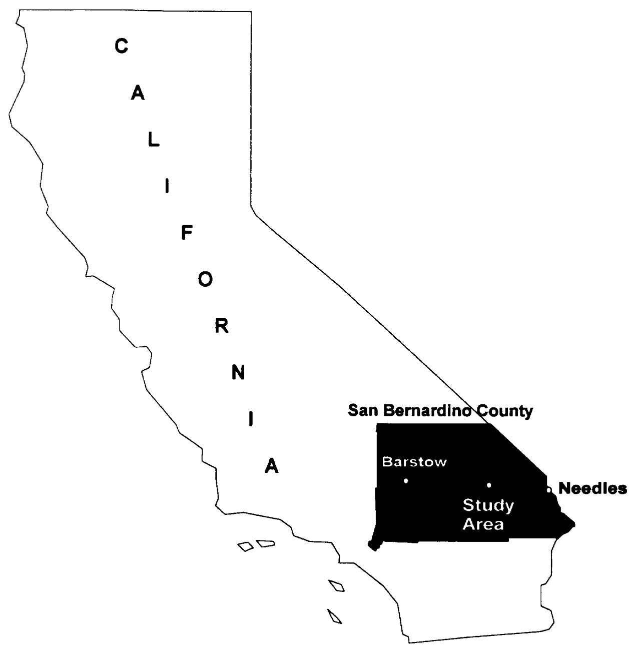

Figure 1. Location of study area

STUDY AREA AND BACKGROUND INFORMATION

Erosion experiments described in this paper were conducted on the Granite Cove Pediment (GCP). The GCP is located within the Mojave National Preserve, immediately south of the Sweeney Granite Mountains Desert Research Center (SGMDRC) (Figure 1, lat. 34°47′, long. 115°39′). Faint relief has developed near the upper elevations of the pediment due to erosion. The pediment does not receive sediment additions because of incision of washes at the upper reaches of the pediment which bypass the pediment surface. The study area is 80 m long and 55 m wide at its widest point. A computer-generated surface of the study area with a four-fold vertical exaggeration is shown in Figure 2A. The land slopes gently to the southeast as a broad ridge divides into two downslope ridges, giving the landscape an inverted 'Y' appearance. Six landscape units were visually defined in this open-ended watershed: summits, shoulders, backslopes, footslopes, toeslopes and washes. Observations of short-term erosional phenomena on these landscape units help explain recent modifications to the pediment and its soils.

By examining surface gravel movements after several storm events, this study tested the following null hypotheses.

(1) After precipitation events, surface gravel movements are similar, in terms of magnitude and direction, as a function of:
   (a) surface shape (convex, flat or convex)
   (b) landscape unit (summit, shoulder, backslope, footslope, toeslope or wash)
   (c) vegetation cover (direct, indirect, or none within original plot frame).
(2) Symmetrical (circular), rather than elliptical, dispersion of surface gravels is found on all landscape units after precipitation events.

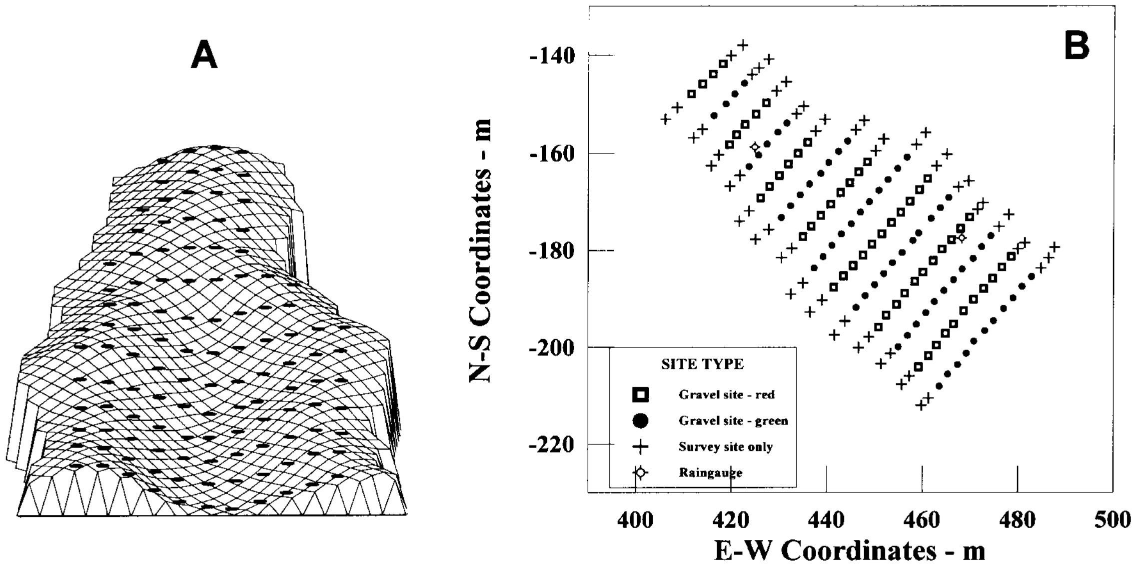

Figure 2. Surface and plan view of gravel dispersion study area. Coordinates are relative to the NW corner of Section 20, T8N, R13E, San Bernardino Baseline

MATERIALS AND METHODS

The main feature of this experiment was to track the movement of painted gravels after several precipitation events. Soil material was collected within the study area (Figure 2A) to ensure similar size and specific gravity of experimental materials. Soil material from the top 5 cm of the soil profile was sieved through a 2 mm sieve. The fine earth fraction (<2 mm diameter) was discarded and particles larger than 20 mm diameter were hand-removed. This size range was selected for convenience in tracking movement and because it represents 10 to 20 per cent of the whole earth by mass in surface horizons in the area (Edinger, 1990). Batches of the 2 to 20 mm diameter gravels were coated with bright fluorescent red or green spray paint.

A grid of 117 points was established in the study area with a spacing of approximately 3 m apart in a SW to NE direction and 6 m apart in a NW to SE direction (Figure 2B). Circular piles (6·5 cm diameter) of 30 g of painted gravels ('gravel spots' or 'nodes') were placed at each point. After establishment of all gravel spots on 3 April 1990, gravel dispersion was quantified on three dates: 10 April, 23 June and 30 August 1990. To monitor precipitation during the experiment, two battery-operated tipping-bucket rain gauges were located within the grid (Figure 2B). Precipitation data were also available from the nearby SGMDRC.

Observations of painted gravel movement were taken using a 1 m × 1 m aluminium frame, subdivided into 100 quadrats of 1 dm^2, placed carefully on the soil surface such that most of the dispersed gravels were within its 1 m^2 area and the painted gravels were not disturbed. The location of the original spot (the origin of an x,y coordinate system) was marked on a data sheet. The number of individual pieces of painted gravels observed in each 1 dm^2 quadrat was recorded. Gravels beyond the first placement of the frame were quantified by relocating the frame appropriately. The distance moved by gravels washed several metres downstream was measured using a metre tape. To depict and calculate centres of mass (vectors), the number of gravels counted (z) in each quadrat was assigned to the central point (x,y) of each quadrat. For example, the coordinates (−5 cm, 5 cm) were assigned to the first quadrat northwest of the origin.

Table I. Precipitation events and data collection dates during experiment

Date (1990)		Precipitation (cm) Granite Cove (daily) (elev. 1300 m)	Study area (cumulative) (elev. 1240 m)
4 April		1·93	
10 April	Data Collection		1·60 (upper), 1·50 (lower) (accumulated between 4 April and 10 April)
16 April		0·05	
24 April		0·33	
28 April		0·23	1·22 (upper), 1·14 (lower) (accumulated between 10 April and 4 June)
9 June		1·80	
10 June		trace*	
23 June	Data Collection		1·83 (upper), lower data not available (accumulated between 4 June and 23 June)
2 July		trace	
10 July		trace	
11 July		trace	
13 July		trace	
14 July		0·84	
15 July		0·03	
16 July		1·93	
6 August		1·19	
9 August		trace	
10 August	Data Collection		5·51 (upper), 4·67 (lower) (accumulated between 23 June and 10 August)
Total		8·33	9·65

*Trace = less than 0·01 cm

On 10 April 1990, the following one-time observation for each gravel spot location were made. Vegetation crown cover influencing the original gravel spot was sketched on data forms and cover was separated into three classes. Class 1 was designated where a shrub's canopy directly covered the original gravel spot. Class 2 was indicated when there was a shrub canopy within the 1 m^2 plot frame, but not overlying the spot directly ('indirect cover'). Class 3 was assigned to a site when no shrub cover occurred within the original placement of the 1 m^2 frame. Overall shrub canopy cover for the study area was about 25 per cent. The surface shape at each node was classified as concave, convex or flat-based on visual observation. Local slopes ranged between 0 and 15 per cent (0° and 8·5°). Each site was designated as one of six landscape positions: summit, shoulder, backslope, footslope, toeslope or wash.

RESULTS AND DISCUSSION

Precipitation events

Fifteen precipitation events occurred during the April to August 1990 study period (Table I). Daily precipitation amounts were recorded at the Granite Cove weather station while cumulative amounts (for each of three time intervals) were read from tipping-bucket gauges at the study site. Gravel dispersion was measured after approximately 1·6 cm, 4·6 cm and 9·7 cm of cumulative rainfall.

Fortunately, for the purposes of this experiment, rainfall between April and August 1990 was unusually high for the East Mojave Desert. A monthly precipitation summary for 1981 to 1990 at the SGMDRC shows that in some years no precipitation was detected in April to July. The total rainfall in April 1990 (2·3 cm) and August 1990 (2·6 cm) was higher than the respective 10-year averages of 0·9 and 2·3 cm. Monthly rainfall amounts for June 1990 (1·8 cm) and July 1990 (2·8 cm) were the maximum monthly amounts recorded for the 10-year period.

Vector lengths as a function of surface shape, landscape unit and vegetation cover

The painted particle method required no sophisticated equipment in the field, but counts were time-consuming, even for particles in the 2 to 20 mm size range. We made the initial assumption that applied paint would not affect the particle's specific gravity or attractiveness to animals. Durability of paint pigments should be tested for field experiments intended to last longer than one year, as the pigments began to fade after about six months. On the other hand, fading pigments may be desirable for research projects in environmentally sensitive areas. Incidental disturbance of particles from burrow construction and sand bathing activities by rodents occurred at seven sites and disturbance by ants was observed at two sites. It is unlikely that animals moved particles systematically. Young kangaroo rats occasionally pouch non-seed items that are similar in size to seeds but this is rare and ephemeral behaviour (Dr Mary V. Price, pers. comm.).

The null hypotheses relative to particle movement were that after precipitation events, surface gravel movements are similar, in terms of magnitude and direction, as a function of:

(a) surface shape (convex, flat, or convex)
(b) landscape unit (summit, shoulder, backslope, footslope, toeslope or wash)
(c) vegetation cover (direct, indirect, or none within original plot frame).

Magnitude and direction of movement is indicated using a vector whose coordinates represent a normalized centre of mass. These vectors were calculated using the following equation:

$$\frac{a_1 v_1 + a_2 v_2 + \ldots + a_n v_n}{\sum_{a=1}^{n} a} = (x, y)$$

where the scalar, a_i, is the number of gravels per dm^2 quadrat (z), and the vector, v_1 is the centre point of each dm^2 quadrat measured from the original gravel spot (x_o,y_o). The resulting vector (x,y) represents the magnitude and direction of gravel movement from the original gravel spot. Vector lengths (VL) were calculated using the distance formula. Equal movement of particles in all directions from a source location would result in a VL of 0 (Figure 3A). In all 117 cases, varying degrees of particle movement were observed. Examples of actual data from a summit and a backslope position and the resulting vectors are shown in Figure 3B and 3C.

The first null hypothesis, that 'similar movements would be found regardless of surface shape', was found to be the case. No significant differences were found when vector lengths were compared among surface shapes, convex, flat or concave (Table II). This is most likely the result of the range of slopes within each shape type. Flat slopes can be level (percentage slope $\sim$0) or sloping (2 per cent, 5 per cent or steeper), just not changing within the reasonably short distances between nodes in this study. The degree of slope influences particle movement (Wright, 1987), so a class containing variable slopes is more likely to have a high variance which leads to non-significant differences between shape classes.

The second null hypothesis, that 'similar movements would be found regardless of landscape position', was rejected for one comparison between landscape positions (Table III). Pairwise t-test comparisons revealed a significant difference between mean summit VL (24 cm) and mean backslope VL (14 cm) (August data, $p = 0{\cdot}10$).

These empirical field results on particle movement can be considered in light of Wright's (1987) model of the redistribution of disaggregated soil particles by rainsplash. Wright's simulations calculated the movement of particles from a central 1 dm^2 grid cell to surrounding cells under varying conditions of raindrop intensity, surface slope, particle size and transferred raindrop momentum. When slope was isolated as a variable, particles moved farther downslope from the origin with increasing slope. Based on Wright's graphical results, vector lengths were calculated for his different slope cases 0·0°, 5·8° and 17·1°

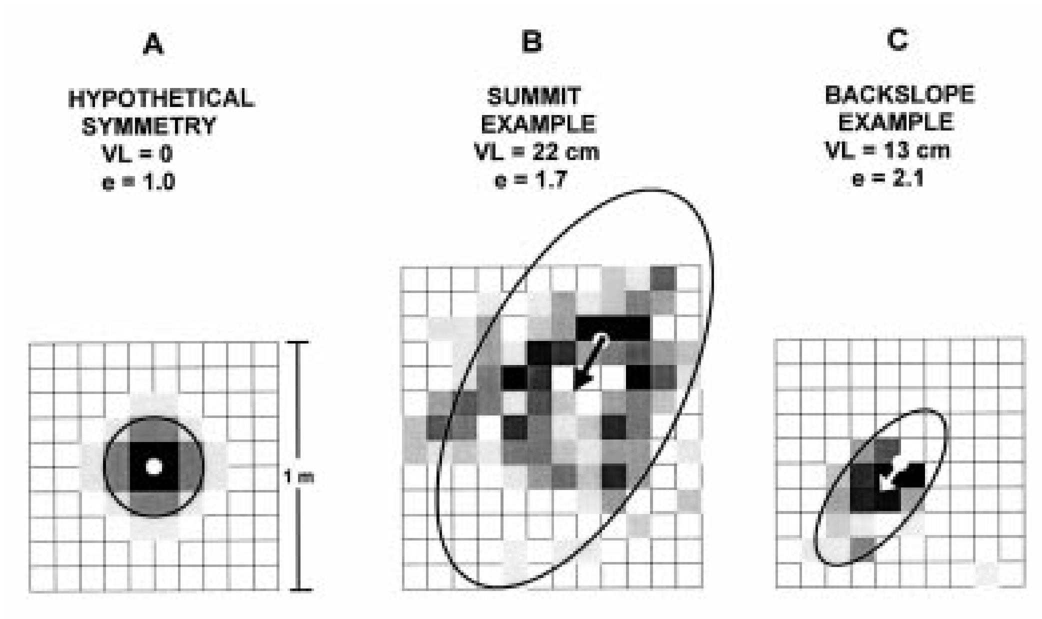

Figure 3. Sketch of gravel dispersion, sampling grid, vector lengths and eccentricities

(0, 10 and 30 per cent) using the maximum number of particles for each size class depicted. The model predicted that at 0 per cent, the centre of mass remained at the origin ($VL = 0$), although particles were splashed as much as 35 cm away. In his simulation with a 10 per cent slope a slightly longer vector length (3·4 cm) resulted as compared to that simulated with a 30 per cent slope (2·8 cm). These results, which are counterintuitive, can be explained in two ways. Since his results were derived from Monte Carlo simulations, chance could result in greater movement for a lesser slope than for a greater slope in an individual comparison. Alternatively, assignment of an equal number of particles to each cell falling in a single range of particles (i.e. all cells having from 100 to 1000 particles assigned 1000) might have led to a miscalculation of the VL. Without the original data it is not possible to say which of these is more likely.

On the pediment, Wright's model would have predicted that painted gravels on backslopes (with slopes approaching 15 per cent) would have moved farther downslope than particles on summits (mostly level), if all other variables could be held constant. Realistically, the field data reflect an integration of many factors including variable angles of rainfall incidence, microtopography, larger particle sizes, turbulent wind gusts, transfer of raindrop momentum, and rainfall intensities. If raindrops fall at a more oblique angle to the level summit but the backslope surface is somewhat in the lee (or perpendicular) to that angle of incidence, it could help explain why the gravel's centre of mass moves farther at summit sites than for backslopes. Thunderstorms were of high intensity on 4 April, 9 June and 16 July 1990, accompanied by high winds.

The final null hypothesis relative to particle movement was that surface gravel movements are similar regardless of vegetation cover. Shrub species providing direct and indirect cover in the study area included: *Yucca schidigera, Lycium* sp., *Ephedra nevadensis*, *Prunus andersonii*, *Haplopappus cooperi, Eriogonum fasciculatum, Ambrosia dumosa, Thamnosa montana, Coleogyne ramosissima, Hymenoclea salsola, Larrea tridentata* and *Tetradymia* sp.

The null hypothesis was rejected. Vector lengths were significantly longer ($p = 0·05$) on sites with no vegetation cover (Class 3) compared to sites with direct cover (Class 1) (Table III). The three cover classes were all significantly different from one another ($p = 0·10$, Duncan's Multiple Range Test), but

Table II. Vector lengths and particles remaining as a function of landscape unit

Landscape unit	Vector length (cm)* April	June	August	Particles remaining August
Summit				
Sample mean	4·7	5·3	24a	187
Standard deviation	4·8	3·0	18	73
Range	1–31	1–11	2–70	49–338
n	34	34	34	34
Shoulder				
Sample mean	3·5	4·9	17a	177
Standard deviation	1·8	3·0	16	54
Range	0–7	0–11	1–54	105–308
n	25	24†	23‡	23‡
Backslope				
Sample mean	4·0	4·7	14a	173
Standard deviation	1·9	2·9	11	63
Range	0–8	0–14	1–40	55–323
n	29	29	27‡	27‡
Footslope				
Sample mean	4·9	10	19a	182
Standard deviation	7·3	18	10	90
Range	1–27	1–65	4–31	81–341
n	11	11	11	11
Toeslope				
Sample mean	3·9	6·3	17a	174
Standard deviation	2·9	2·8	13	45
Range	1–11	1–11	0–32	101–235
n	9	9	8†	8†
Wash				
Sample mean	3·2	16	21a	116
Standard deviation	1·4	36	17	64
Range	1–5	1–111	0–50	27–209
n	9	9	8†	8†

* Vector length means followed by the same letter are not significantly different ($p = 0{\cdot}10$) using Duncan's Multiple Range Test
† One site washed out
‡ Data missing for one site
§ Two sites washed out

with pairwise comparisons ($p = 0{\cdot}10$), sites with direct cover (Class 1) were not significantly different from sites with indirect cover (Class 2). The farthest extent of movement for particles located in the direct canopy of shrubs was only 15 to 25 cm from the original spot. These results indicate that gravel-sized particles under vegetation are significantly protected from rainsplash transport to regions outside the plant canopy cover. The absolute count of particles remaining (Table IV) indicates that significantly fewer particles were recovered on sites with direct plant cover (Class 1) compared to sites with no shrub cover in the intial plot (Class 3) ($p = 0{\cdot}05$). Painted gravel particles under plant canopies were probably buried by a net accumulation of particles splashed in from outside the canopy.

Similar phenomena were observed by Parsons *et al.* (1992) who used sediment traps and a rainfall simulator to demonstrate that more sediment was splashed towards shrubs than away from shrubs on semi-arid piedmont hillslopes. By examining soil profiles, they hypothesized that mounds under shrubs were formed by a combination of net accumulation of mostly sand-sized particles under shrubs and net removal of materials by overland flow in inter-shrub swales. The present study provides further evidence

Table III. Vector lengths as a function of vegetation cover

Vegetation class	Vector length (cm) April	June	August*
1, direct cover			
Sample mean	4·6	7·2	11b
Standard deviation	5·4	14	8·2
Range	0–27	0–65	1–27
n	20	19†	20
2, indirect cover			
Sample mean	3·9	7·2	17ab
Standard deviation	2·0	16	15
Range	1–11	0–111	0–61
n	46	46	44‡
3, no cover			
Sample mean	4·1	5·6	24a
Standard deviation	4·1	2·7	15
Range	0–31	1–12	1–70
n	51	51	47‡

* Vector length means followed by the same letter are not significantly different ($p = 0{\cdot}05$) using Duncan's Multiple Range Test
† Data missing
‡ Sites washed out

Table IV. Particles remaining as a function of vegetation cover (August data only)

Vegetation class	Particles remaining*
1, direct cover	
Sample mean	147b
Standard deviation	66
n	20
2, indirect cover	
Sample mean	172ab
Standard deviation	67
n	44
3, no cover	
Sample mean	188a
Standard deviation	66
n	47

* Means followed by the same letter are not significantly different ($p = 0{\cdot}05$) using Duncan's Multiple Range Test.

that rainsplash erosion, coupled with the protection afforded by shrub canopies, is probably a more important process in coarse-textured soils than aeolian processes or isolation of relict surfaces (Rostagno and del Valle, 1988) in explaining the formation of shrub mounds.

Dispersion symmetry

The null hypothesis related to particle dispersion was that all landscape units have symmetrical (circular), rather than elliptical, dispersion of surface gravels after precipitation events. Using Wright's

Table V. Eccentricity values as a function of landscape unit (August data only)

Landscape unit	Eccentricity	
	With 'outliers'	Without 'outliers'
Summit		
Sample mean	2·7	2·7
Standard deviation	1·2	1·2
Shoulder		
Sample mean	2·9	2·8
Standard deviation	1·5	1·5
Backslope		
Sample mean	4·6	2·9
Standard deviation	9·3	1·5
Footslope		
Sample mean	3·3	3·3
Standard deviation	1·8	1·8
Toeslopes		
Sample mean	23·7	2·7
Standard deviation	62·9	1·7
Wash		
Sample mean	255	4·9
Standard deviation	674	6·3

(1987) model for rainsplash redistribution one would expect the centre of mass to remain at the origin and the dispersion of gravels to be circular if a surface had no slope, no overland flow (only raindrop impact), and if raindrops hit the surface from directly overhead (perpendicular) (Figure 3A).

In this study, local slopes were not measured at each gravel spot and the angle of rainfall incidence was not recorded. However, landscape units were qualitatively assigned based on their relative position and slopes. Arguably, summits are most likely to have the most symmetrical gravel dispersion because of the following combination of features: flattest shapes, least sloping and least likely to receive runoff from other areas. Backslopes might vary in shape, but are most likely to have the steepest slopes. Therefore, backslopes would be more likely than summits to have elliptical gravel dispersions because of increased chances of overland flow. Washes would be most likely to receive overland flow, and therefore would have the least symmetric dispersion patterns.

Deviation from symmetry is described here by an eccentricity value (e): the ratio of variances of the major and minor axes of an ellipse. In the case of a perfect circle, major and minor axes are equivalent and the eccentricity is equal to one. Eccentricity values increase as ellipses become more elongated or 'cigar-shaped' (Figure 3).

To calculate and compare eccentricities of gravel dispersion as a function of landscape position, the following procedures were followed. All data points (z values) in gravel spots were mathematically rotated such that the vector (centre of mass) coincided with the 1:1 line in the positive (1) quadrant of the (x,y) coordinate plane using the rotation equations:

$$x' = x \cos\theta + y \sin\theta \quad \text{and} \quad y' = -x \sin\theta + y \cos\theta$$

The following values were then calculated for each gravel node's dispersion (August only): correlation coefficient, ρ, variances, σ_x^2 and σ_y^2, and ratio α, equal to σ_x^2/σ_y^2. These values were used in the following equation to calculate the eccentricity, e, of the ellipse (Dr David Strauss, pers. comm.):

$$e = (1 + \alpha + \mathrm{sqrt}((1-\alpha)^2 + 4\alpha\rho^2))/(1 + \alpha - \mathrm{sqrt}((1-\alpha)^2 + 4\alpha\rho^2))$$

A summary of mean eccentricities, with and without outlier particles, is found in Table V. There were seven painted particles that moved from about 3 m to as far as 50 m downslope during the four-month

observation period, most likely transported by overland flow. These 'outliers' travelled from sites that were in the vicinity of washes or small rivulets. In general, gravel dispersion patterns become more distorted (higher eccentricity values) in a progression of landscape units from the summit to the wash. The most striking contrast is eccentricity values occurs in the wash, where gravel particles were found tens of metres downstream. However, paired comparisons of landscape unit eccentricities were not significantly different because of high variances with or without outliers in the analysis. Although the mean backslope vector length is significantly shorter than the mean summit vector, the backslope eccentricity (mean = 4·6) indicates that the dispersion pattern is indeed influenced by the steeper slopes (summit mean = 2·7, shoulder mean = 2·9). Elongated dispersion patterns in the toeslopes and washes are probably caused by overland flow. Relatively lower particle recovery values confirm that deposition and burial are important processes on lower landscape units.

SUMMARY AND CONCLUSIONS

Rather than depicting analogue pictures of gravel dispersion patterns directly from sampling grids, this paper presents two descriptive statistics to describe the extent to which gravel particles at the soil surface move in response to precipitation: (1) the centre of mass vector, which indicates direction and magnitude; and (2) eccentricity, a ratio of variances of the major and minor axes of an ellipse. Theoretically, an infinite number of particle arrangements can result in a centre of mass vector or eccentricity value. But, when centre of mass vectors and eccentricity values are considered together along with other descriptors, such as ranges of particle movement and percentage particle recovery, more definitive interpretations and comparisons can be made.

Surface shape (convex, concave or flat) had no significant effect on painted gravel movement. Centres of mass moved significantly farther after about 9·7 cm of cumulative precipitation on summits (vector length = 24 cm, 34 nodes observed) compared to backslopes (vector length = 14 cm, 27 nodes observed) over a four-month period. Gravels directly beneath shrub canopies were protected significantly from rainsplash erosion. Lower recovery of particles under canopies suggested burial with a net addition of particles from the outside being splashed in. This study lends more support to the hypothesis that rainsplash and plant cover protection are important processes in shrub mound formation, especially in gravelly soils where wind erosion may not be as effective as water erosion. While not significantly different, gravel dispersion patterns were most rounded ($e = 2{\cdot}7$) on summits and became increasingly 'cigar-shaped' downslope, especially in washes ($e = 4{\cdot}9$).

The following depicts the degree to which different landscape units on the upper pediment experience rainsplash and overland flow in the absence of plant cover or small-scale rivulets, based on the results of this study.

RAINSPLASH EROSION

Most - - - - - -	- - - - - -	- - - - - - **Least**
Summits	Shoulders Footslopes Toeslopes Washes	Backslopes

OVERLAND FLOW

Most - - -	- - -	- - -	- - -	- - -	- - - **Least**
Washes	Footslopes	Backslopes	Toeslopes	Shoulders	Summits

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